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JPL COMMON THREADS WORKSHOP II
SUMMARY REPORT
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Introduction

The second Common Threads (CT) workshop was held on 25 July 1997 in an off-lab environment. The premise and the theme of this series of workshops is that "common threads" exist which appear in one spacecraft program after another. These threads may take the form of similar flight and test failures, identical failure physics, recurring programmatic issues or even an occasional serious oversight. These problems are understood and often solved on one program, but the knowledge is frequently not passed to another program with a similar problem, and the cycle repeats.

The second workshop was introduced by Jim Clawson, Manager of the Reliability Engineering Office. CT Workshop II was sponsored by NASA Code Q through the Division 5X Assurance Technology Project Office (ATPO) as part of the Flight Performance RTOP. These workshops provide another forum on the history of the Laboratory. As Chairman of the Lessons Learned Committee, Clawson is intensely interested in conveying the historical lessons from past programs to today's spacecraft system developments. He considers it a primary responsibility of Reliability Engineering Office personnel to understand the history of the Laboratory and to infuse its lessons into new programs.

Clawson started by relating this year's CT Workshop to the one held last year. The intent of these workshops is to look for problems or situations that recur from program to program, so-called "common threads." Last year, the workshop presenters were primarily current or former Program Managers, and the common threads that emerged tended to focus on programmatic issues. The CT Workshop I Summary Report (JPL D-13776) is one of the Flight Performance Assessment reports available on the JPL Reliability Engineering (Section 5053) home page (http://oak.jpl.nasa.gov). This year's workshop followed the same format as before, but the emphasis was on design issues, with Engineering and Science Directorate personnel being the primary presenters and invitees.

Format of this Report

Many of the presenters presented "war stories" from their own personnel experience on JPL spacecraft programs. Several chose to present "lessons learned" from their general experience and omitted specific war stories. A strictly chronological presentation of the discussions would lack organization and might not illustrate the common threads that intertwine through the experience of the presenters. Some of the presenters spoke from view graphs; others did not. In the interest of brevity, the content of the view graphs has been incorporated into the body of this report, but the view graphs themselves have not. The workshop was video taped and a number of participants took notes. This report is a compilation of all of those contributions.

As would be expected, there was not complete unanimity in the opinions voiced during the workshop, but there was substantial agreement on many issues. The approach taken in this report was to consolidate the common threads from all of the presenters and the discussions that followed. War stories related to a specific common thread are presented in tabular format along with the lessons learned and the presenter's recommendations. Related comments are presented together to reinforce a common thread, but may have occurred at any time during the day. It is hoped that not too much of the spontaneity and "feel" of the workshop is lost in this consolidation process.

Summary

From the presentations, a number of 'common threads' emerged. As might be expected, there was significant commonality between the threads from the first and second workshops. The threads that characterized the first workshop fell into the following general groups:

Communications Issues at all Levels.	Hardware Interfaces
Contractual Interfaces	Heritage and COTS Issues
Parts Issues	Programmatic Issues
ATLO and Launch Site Issues	Product Assurance Issues

Some of these general groups were approached from a different viewpoint and emphasized different aspects of an issue in the second workshop. For example, *Hardware Interfaces* in the first workshop focused on 'war stories' where a miscommunication occurred across a poorly understood or improperly documented hardware interface and created a potentially serious mission-threatening situation. *Hardware Interfaces* in the second workshop included fewer war stories and were addressed as part of the overall issue of Configuration Management on a spacecraft program. For example, the presenters discussed minimum documentation requirements, errors that were made, what could have been done better, pitfalls and approaches to avoid.

Some significant new threads were identified by the 3X system and subsystem developers who spoke at Common Threads Workshop II. These included:

System Level Thinking	Subsystem Development Issues
Teamwork	Configuration Management
Fabrication and Production Issues	Collocation
Software Development Issues	Vendor Issues

These new threads generally fell within one of the groups that had been identified during the first workshop. For the sake of continuity, the new threads are presented here under the appropriate group headings from the earlier report. Where the thread has been identified before, the same titles are used as in the first workshop report.

Communications Issues

There was general agreement that communications, specifically intra-project, inter-project and communications from generation to generation are critical issues facing the laboratory. Rob Manning started his Pathfinder presentation by saying that "JPL lives on its war stories. Common threads weave the institution together as a culture. Although Pathfinder may have stretched the fabric 'to the left,' they still took the JPL culture with them to Mars. " Kim Reh suggested that we need a "mentoring machine" for the Laboratory. Steve Bolin said that there should be a Tech Division for Project Managers, where they can interchange ideas and renew their knowledge of the technology. (The Space and Earth Science Programs Directorate Deputy Director [Tom Gavin] has recently initiated monthly Project Manager meetings which go a long way towards this goal.)

The “war stories” related to communications were mostly instances of failure by the projects to take advantage of knowledge that already existed at the laboratory but which required them to seek it across some organizational boundary they chose not to cross. Concerns were expressed by the presenters and the audience over the loss of “grey beards” due to attrition and downsizing. Some critical skills are being lost such as pyrotechnics expertise and familiarity with Cape launch operations.

There was considerable discussion about how to get people to access the “lessons learned” information that exists at the Laboratory. JPL and NASA “lessons learned” home pages, as well as a Mars Pathfinder (MPF) lessons learned summary are already available on the Internet. John Koch believes that we need to build the lessons learned and design rules into the Design New Products (DNP) process before lessons learned can be fully appreciated and implemented on new programs, Jim Clawson pointed out that one objective of DNP is to make the lessons learned available.

Hardware Interfaces

The topic of Hardware Interfaces was expanded to include all hardware configuration management (CM) issues. Again, failure to communicate a full understanding of the design constraints at hardware interfaces was the critical issue. Carl Buck described the Mars Pathfinder (MPF) incident in which debris from an explosive delay line on the Delta launcher clouded the Sun Sensor window, nearly disabling both sensors and jeopardizing the entire MPF mission. The problem had been recognized on the Mars Global Surveyor (MGS) program, but the message wasn't conveyed to the MPF designers.

The ’Right’ Amount of Hardware Documentation on FBC Programs. The issue of how much hardware documentation to do on Faster-Better-Cheaper (FBC) missions received much discussion. MPF policy was to do only as much configuration management (CM) as they had to and no more. MPF’s functional requirements documentation was minimal, and largely paperless. Rob Manning stated that Interface Control Documents (ICD) were very important and a definite exception to their minimal documentation rule.

Still, Buck's view was that they had gone too far in some cases. For example, the MPF project allowed release of red line drawings. Carl felt that we shouldn’t do this on future FBC programs. He also believes that people were pulled too quickly at the end of MPF. As a result, some important configuration control items were left unfinished

Spacecraft/ Simulator Interfaces Several of the presenters mentioned that there needs to be a fuller appreciation of the capabilities and requirements of Deep Space Network (DSN) operations on the part of the design team. The test bed needs to simulate telecom and DSN actions and response times to ensure integrity of the entire mission sequence including data acquisition operations

Contractual Issues

An instance in which an contractual relationship led to increased cost on the Topex transponder development program was presented by Tom Komarek. Although Topex was a highly successful program, Komarek believes that closer monitoring of the radio subcontractor would have saved time and money. There was an 18 month delay and several million dollars spent in correcting preventable problems, but JPL was reluctant to get between the prime and the subcontractor.

Carl Buck discussed database transfer issues when JPL and the prime contractor don’t use the same CAD system. On SIR-C they were unable to convert to Computer Vision after considerable expense and reverted to paper documentation of interfaces. In the future, Carl warned that we should use the same CAD platforms as the prime contractor; otherwise use paper!

Heritage and COTS Issues

John Slonski discussed the Laboratory experience with Star Trackers which he considers one of the most vexing inheritance problems. Among the most significant problems have been a disturbing habit of tracking dust and debris in addition to stars. The new ones are supposedly better, but it will take years of “perfect” performance to be proven.

Regarding Commercial Off the Shelf (COTS) issues, Slonski and several other participants quipped that “The only thing you get off the shelf is dust!” Tom Komarek added that it would be nice if he could buy his telecom radios from Radio Shack, but unfortunately he can’t. The sensitivity requirements are too demanding. Costs are driven up because the demand for such high performance transmitter/receivers isn’t great enough to bring prices down.

Several examples of the hazards in "trying to make something that's good enough just a little better" were offered. Komarek discussed a relatively minor ground strap problem on Magellan which was very costly to rework, because the rework itself led to so many problems. He considered the cure worse than the disease. Les Compton described a design change that was made to the MPF retro rocket propellant from 16% aluminum to 2% aluminum. The change was made to reduce contamination at the Mars landing site, but was made without sufficient appreciation of the repercussions. During testing they found that mechanically induced, coupled internal oscillations among the three rocket motors caused a burn rate anomaly. Ultimately, they reverted to the 16% aluminum formulation. Contamination of the landing site wasn’t a significant issue because of the large distance between the initial impact point and final lander location as a result of airbag bouncing.

Parts Issues

Combining parts buys can save large amounts of money. Kim Reh pointed out the Cassini inheritance to other missions, especially ASICs. Buying in greater quantity provides leverage, but there needs to be Phase A and B (i.e., Conceptual phase) coordination of projects to take advantage of potential multi-use ASICs. Other parts issues concerned ensuring that a common database for part footprints is used by printed wiring board designers, the fabrication group and procurement to avoid messy problems that occur when purchased parts don't match the board layout.

Jim Marr told a war story about one case when a parts problem actually saved a mission. During the Galileo development, many problems occurred with the TC-244 memory chips The TC-244 had to be scrapped in favor of a relatively unproven RAM chip that had much less test history, but in the end, the problems turned out to be fortuitous. As a precaution, Tom Gavin, the Product Assurance Manager, was responsible for doubling the amount of memory on-board. Without this added memory, Marr stated that it would have been impossible to do any of the data compression that was needed to salvage the Galileo mission after the High Gain Antenna anomaly.

Programmatic Issues

Several of the presenters offered words of caution about assuming too much risk on current and future programs. In the first workshop the Program Managers had referred to this as "sell pressure," i.e., the pressure they feel to take unwanted risks to "sell" their programs to NASA. Rob Manning had been involved with Galileo and Cassini, primarily with the AACS and CDS systems. He said that there was really never any question during those developments about whether the missions would ultimately succeed. He referred to Pathfinder as a "scary ride." They were always uncertain about whether the systems would work or not.

Tom Komarek observed that we are going through a "gutsy" period at JPL. Several projects are assuming higher risk than we were previously willing to take. He believes we won't be able to repeat this very often, because of the need to continuously develop our ability to acquire better, more accurate scientific data. We need to reinstate our commitment to depth, discipline and rigor in support of the sciences and develop the new tools we'll need to do it.

Collocation

There was considerable discussion on the subjects of collocation and concurrent engineering team issues. Collocation was universally praised as a way to achieve an "intellectual critical mass" in which designers can freely interchange ideas and establish a systems approach to design. This occurs because the designers hear and are involved in the solution to each other's problems. The subsystem designers were equally in favor of collocation but were perplexed at how to achieve it in a practical sense. There are more projects than there are experts within a given technical discipline; this means that the technical experts must be assigned to more than one project at a time. Clearly, they can't be collocated with multiple projects simultaneously. Additionally, the FBC programs frequently can't support a full time technical specialist in every discipline. Collocation is an ideal to be sought on critically important projects but can never be a universal solution.

System-Level Thinking

Thinking “beyond your interface” was praised by several of the presenters. Subsystem designers need to consider the system-level implications of the application of their hardware. They may be aware of issues or problems not apparent to the systems designer which could be avoided by a different physical implementation, part selection or design approach. Systems-level thinking may be facilitated by collocation, but it needs to be done even if the designers aren’t collocated. In general, the project people had a better impression of the level of “system-level thinking” that existed than the line organization people did. Some line organization technologists voiced the opinion that much more could be done to acquaint the subsystem designers with all of the mission objectives so the designers would see opportunities to think “outside the box,” i.e., beyond the limits of their normal way of thinking.

Teamwork

There was a definite difference in the way the subsystem developers and line managers perceived the level of teamwork achieved on programs as compared to the project people. The project people were generally satisfied with it, but the subsystem designers often felt left out of the process. There were several complaints from Engineering and Science Directorate (ESD) personnel that the project-subsystem interface was generally a one-way street, with the designers going to the project office but rarely the other way round. This was an impediment to the idea of “systems” thinking by the subsystem designers.

Kim Reh addressed the teamwork issue from the viewpoint of the avionics subsystem technologists. He emphasized the need to create an attitude of team ownership between the projects and the subsystem developers and to build strong teams. Communications must be free and open. He also emphasized the need for "tough love," i.e., strong and decisive project management. He believes that the Program Element Managers (PEM) are very good technically, but not so good in managing schedule and funds. He believes that it is necessary to include industry in the new FBC teams, but the number of contractors needs to be kept to a manageable number. He believes there were too many contractors to manage the DS-1 3D stack program effectively. The design was too complex which led to cost overruns and late deliveries.

Budget and Schedule Reserves

Approximately forty percent (40%) of the flight system budget on MPF was reserved for unplanned events. A significant portion of this reserve was spent performing tests to resolve development issues that evolved as the ATLO program progressed. This issue was discussed extensively and reported in the first CT Workshop. Ironically, the reduced level of documentation and the less structured program on MPF may make it more difficult to transfer the MPF experience to other programs. Manning said that the process is transferable, but implied that the detail may be lost. It is obviously in the spirit of the Common Thread Workshops to suggest that an opportunity exists to capture much of MPF experience while it is still fresh. The cost and technological benefit to future programs could be enormous.

Hardware/ Software Integration Issues

Software development and integration issues were not discussed at the first CT Workshop, but Jim Marr presented his views on the subject, based on his experience with the Gallileo recovery effort and the DS-1 software development. He said that software issues are normally not given the same level of attention as hardware issues. As systems become more complex, software issues become increasingly important. Imbedded software systems need as much attention as the hardware. Software development has to be run as a project with all of the appropriate project controls. Flight and ground software must be treated as a system, with proper partitioning of functions between the two entities. Likewise, we need a better way of partitioning functions between H/W and S/W to optimize the system and we need to develop tools to do that.

ATLO and Launch Site Issues

Vince Wirth pointed out that there is a tendency to complicate the activities at the Cape which leads to delays and large increases in cost. He emphasized the need to separate the "Must Do" activities from the "Like to Do" activities at the Cape. Activities such as propellant tank loading, pyro installation, and mating with the launch vehicle must be done at the Cape. However, he thinks some "Like to Do" activities could be avoided at the Cape such as Final System Test, DSN compatibility testing and spin table and CG operations.

Wirth advised that a person knowledgeable about KSC should be a member of the design team. He recommended that spacecraft be designed to minimize the number of pieces shipped and re-assembled at KSC. He also recommended that spacecraft should be designed so parallel operations can take place, for example, by separating the propulsion system from the electronics, so the electronics can be tested while hazardous operations are taking place elsewhere. He recommended combining hazardous operations on the pad. It is cheaper and faster to do all hazardous operations in one place.

Product Assurance Issues

Much of the Product Assurance discussion centered on the MPF program and how they had handled the redundancy issue. Manning said there is a perception that MPF was a "single string," i.e., non-redundant system. While much of MPF was single string, there was selective redundancy. There were dual Sun Sensors, entirely dual NASA Standard Initiators (NSIs) for the entry-descent-and-landing (EDL) sequence, dual power strings for the pyros and other redundant elements.

MPF used a simple, straightforward process for determining which subsystems needed to be redundant. They formed a team of design and reliability people. The team estimated a rough probability of failure for each subsystem and ranked it low, medium or high. Then they considered the mission impact of the failure as low, medium or high. Where there was a high probability of failure and a high mission impact, they did something about it, either to reduce the probability of failure or reduce its impact.

Clawson observed that the Pathfinder reliability growth projections indicate that more problems should have occurred. A MPF group is being formed to review the early program decision process to see what was done *right* so that important lessons learned can be carried over to new programs. There was also considerable discussion of the number of Single Event Upsets (SEUs) that have been seen on MPF. To date, they have seen none which is well below the expectation and raises a question about the validity of the overall SEU modeling process.

Fabrication and Production Issues

Fabrication and production issues were only touched on in the first CT Workshop, but were considered by Dennis Carpenter in the second. In Dennis' opinion, less rigor is being applied than in the past, and some of the fabrication risks being taken are not good ideas. New technology presents new problems. Devices are smaller and harder to fabricate and inspect. Contamination is a severe problem. Ball grid arrays, for example, are difficult, because the solder bonds can't be inspected.

There is a persistent problem with cabling, which doesn't receive enough attention in the design. Cabling generally consumes more volume than expected. The routing of cabling becomes a problem if it isn't planned for early in the design.

On the other hand, some processes are much better. There are far fewer problems with printed wiring boards (PWB), because suppliers have well controlled processes. Part quality is generally good. Nevertheless, there is still a variety of chronic problems. Flexprint cable connections still occasionally get laid out upside-down . Printed wiring board designers sometimes use a different footprint for a part than the procurement people buy. Suppliers change processes such as cleaning which later leads to outgassing during thermal/vacuum tests.

Dennis' advice was to involve the production people early in the design process. Make sure the printed circuit designers and the procurement people are using the same footprint for parts. Consider cabling as an integral part of the design rather than an afterthought. Use known, qualified vendors, and requalify them frequently. What was good yesterday isn't necessarily good today.

Discussion

Tables 1 through 9 present the common threads that were discussed during CT Workshop II, along with lessons learned and some approaches that the workshop participants believe will be useful in addressing them. Each table presents one of the major groups of common threads, e.g., Interfaces, Parts, or Communications issues.

The presentations ranged over many subjects, with individuals in the audience freely making comments from the floor. In a sense, the tabular format used in this report implies an order in the discussions that wasn't really there. What has been done in the tables is to gather related comments that were made throughout the day and place them together. The intent is to capture the ideas that were presented, not to neatly resolve every issue. Nevertheless, a serious attempt has been made to deduce the implications of what was said and to write them down.

There are four column headings in the tables. The definition and the general purpose of each column are described below:

Common Thread - an idea or an issue that was discussed and seemed important enough to capture. Often it was truly a "common" thread in that several different persons discussed the same issue. In many cases, a similar thread had already been identified in the first workshop. When this occurred, the precise text from the first CT Workshop report was used to describe the thread. Even if only one war story or comment was given, an attempt was made to capture all significant ideas presented at the workshop, either by the presenters or the participants.

War Stories - anecdotal stories related to the common thread and drawn from past or current programs. Some of these stories recount failures from previous programs and the circumstances that led up to the failures. Others are examples from current programs that describe problems in dealing with the new Faster-Better-Cheaper (FBC) guidelines or ways the projects have successfully dealt with them. Almost anything qualified as a war story, so long as someone was willing to tell it. Just as with real war stories, there is room for a difference of opinion. An effort was made to present all stories, even though their implications might seem to conflict.

Lessons Learned - the conclusions that can be drawn about a common thread that may have general implications for future programs. Lessons learned were not always explicitly stated by the participants but were sometimes obvious extensions of their thought process. In these cases, the lessons learned are the writers' opinion of the implications, based on what was said. To distinguish them from the comments of the participants, they are preceded with the notation (Implied), while the comments of the workshop participants are preceded by their (Name).

Corrective Strategies - strategies or actions that can be undertaken to resolve the issues posed by the common thread. Where these are suggested actions of the participants, they are preceded by the proposer's name. Where they are the writers' extrapolation of the thought process as to what corrective strategies may be effective, they are preceded by the notation (Implied). It was considered important to write all of these strategies down; no apology is made for "explaining the obvious."

Numbering of Entries in the Tables

The numbers in the tables have no special significance; they only serve to separate different thoughts. Moreover, no attempt was made to use the numbers to carry thoughts on a specific topic from one column to the next. This would have added another level of complexity to the tables. It would also imply that each of the common threads and their related thought process led to some neatly resolved conclusion. This was certainly not the case, and to imply that it was so would do a disservice to the spontaneity and spirit of free interchange at the workshop.

Table 1 Common Threads - Communications

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Inadequate Training of Critical Personnel.	Pathfinder Telecom (Manning) (Pathfinder) They made some "cockpit errors. They needed to send uplink commands when the sun was high and the solar cell output was maximized. Unfortunately, earth is low on the horizon at that time. . They made two "timing errors by sending uplinks to the spacecraft before the spacecraft was ready, and so lost those passes. (Wood) (Pathfinder) Forty-five minutes after Pathfinder was launched, the initial acquisition with Goldstone occurred. Wood watched the first telemetry data come in and was able to determine the spacecraft rotation rate and angle just from the variation in the telemetry data stream, i.e., without any telemetry data reduction. Some of the other personnel waiting to analyze the downlink data were surprised that he could do this and do it before they could analyze their own data. • Mission planners were unprepared for communications issues in surface operations • Telecom operations personnel were only peripherally involved in planning • The first tangible feedback to mission planners occurred after landing. • There was no review of DSN configurations and required actions before sequences were approved and sent. • Too many people were talking to the DSN which guaranteed confusion. Mistakes were (needlessly) made	1. (Wood)Improved interface with the DSN and training in planetary surface operations might have solved the "earth set" problem and obtained data on all passes. 2. (Wood) "Comm links have two ends. They don't end at the spacecraft antenna. The ground end possesses capabilities and those capabilities are evolving in time. 3. (Wood) Earlier coordination with the DSN would have resulted in a better planned operations interface. 4. (Gibbel) Nobody has time for lessons learned at the beginning of a project. 5. (Gibbel) Training similar to Vince Wirth's ATLO School for the people involved in the PF T&E program can be beneficial.	1. (Wood) Closer interaction of the Project with the telecom and DSN personnel would help the projects solve some data recovery problems more elegantly. 2. (Wood) Knowing and fully utilizing the capabilities of the DSN, provides opportunities for inherent redundancy and will improve overall reliability on programs. 3. (Implied) Consider training classes as a quick way to train a project team. .
Inadequate Training of Critical Personnel. (Continued)	1. Wave Guide Transfer Switch (Manning) (MPF) They were worried that the wave guide transfer switch would fail. In fact, it did fail, but only because the testers damaged it. There were far more failures induced by the testers than due to failures of the hardware.	1. (Implied) 'Cockpit Error' can damage even reliable parts. 2. (Implied) Test crew training and walkthroughs are essential.	1. (Workshop I) (Implied) Rehearse critical operations. 2. (Workshop I) (Implied) Use the same crew that rehearses. Put names in procedures!

Table 1 Common Threads - Communications (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Inadequate Training of Critical Personnel. (Continued)	**Freon Pumps** (Manning) (MPF) During a launch simulation, they turned on the Freon pumps without any Freon in them. Freon acts as a lubricant and coolant and without it the pumps overheated during test. They replaced the pumps which was not easy, because they had to undo welds. As things turned out they probably wouldn't have needed to. The "burned up" pumps have now been working continuously for over a year	1. Test errors can occur when there is inadequate oversight.	1. Perform peer review and walk through of development test procedures that involve flight hardware.
Inadequate Training of Critical Personnel. (Continued)	**(Slonski) (Magellan)** **Magellan Book Drop Test** An accident occurred on Magellan that turned out to be serendipitous. They were doing a test of the Venus Orbit Insertion (VOI) software, injecting several intentional faults and watching the way the fault detection software responded, when someone accidentally dropped a book on a console keyboard. This invalidated the test, however they didn't cancel the test, but continued. The Flight Processor software did things it wasn't supposed to do, which led them to make changes in the fault detection/correction routines. John said that this kind of accidental fault is more like what occurs in flight than the failure modes one thinks of.	1. Sometimes errors can be fortuitous.	(Slonski) Lesson: Take advantage of accidents. Look closely at what happens. Sometimes, it can pay off.
Inadequate Training of Critical Personnel. (Continued)	**New Vocabulary associated with Autonomous Flight** (Marr) (DS1) also mentioned that there was a lot of new vocabulary associated with the Remote Agent approach. The ideas weren't necessarily that new, but the words were. This tended to alienate the Core Engineering and the Test Teams. Marr believes that a lot of this was unnecessary, and that a more conventional and agreed upon vocabulary would have caused fewer problems.	1. New terminology can be a source of miscommunication and can impact the development time adversely.	1. Be careful about introducing new terminology. Avoid it whenever the old will do. Communicate it clearly to all development activities when it must be introduced.

Table 1 Common Threads - Communications (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Failure to convey “lessons learned” from one program to the next and to all program elements, including the contractor and subs.	1. (Manning) (Pathfinder) observed that “JPL lives on its war stories”. Common threads weave the institution together as a culture. Although Pathfinder may have stretched the fabric “to the left,” they still took the JPL culture with them to Mars. 2. (Komarek) (Telecom) believes that meeting for dialog like the CT Workshops is necessary for success. 3. (Buck) (Pathfinder) considers it necessary to capture lessons learned. 4. (Koch) (Audience) observed that even though the Lessons Learned are available, people don’t read them. 5. (Palmer) (Audience) Lots of the “Gray Beards” are leaving the Lab. 6. (Shinbrot) (Audience) (Implied) The degree to which formal Lessons Learned become important is partly a matter of scale. He cited an example from his experience at Bechtel in designing power plants. At a normal rate of 2-3 plants per year there was little emphasis on lessons learned. However, when they went to 20 - 30 per year and got many more people involved, they had to formally convey experience from one PM to another. They made each manager stand up before the others and discuss what went right and what went wrong on each power plant.	1. (Reh) We need a “mentoring machine” for the Laboratory. 2. (Shinbrot) (Implied) Large scale operations such as JPL’s require formal processes for conveying “Lessons Learned.” 3. (Cornford) The number of lessons learned tends to infinity. (Implied) No one can know them all.	1. (Koch) We need to build the lessons learned and design rules into the DNP process. 2. Brian Muirhead has chaired a “Lessons Learned” presentation on Pathfinder which is available on the Internet. 3. (Clawson) The thrust of DNP is that they will make the lessons learned available. 4. (Shinbrot) (Implied) Maintain a formal process for conveying Lessons Learned. 5. (Bolin) There should be a Tech Division for Project Managers, where they can interchange ideas and renew their knowledge of the technology. 6. (Cornford) (Implied) Use the guidance you have but use it with forethought. Think before you act • If the old guidance doesn’t work, don’t use it. • Consider the root causes of failure and act accordingly.

Table 1 Common Threads - Communications (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Failure to convey "lessons learned" from one program to the next and to all program elements, including the contractor and subs (Continued).	**PF Sun Sensor Anomaly** (Manning) As Pathfinder first came into the sun about 40 minutes after launch, neither of the two redundant sun sensors picked up the sun. There was some panic at this point. They determined that debris from an explosive delay line in the launch vehicle used to deploy the yo-yo system on the Delta upper stage had clouded both sun sensors. The yo-yo system deploys two lead weights on tethers that de-spin the spacecraft from 70 to 12 rps. The PF team had been unaware of the pyrotechnic delay line on the Delta, so this was a complete surprise. It led to a common cause failure in which both redundant sun sensors were temporarily disabled. Fortunately, the sun sensor that was farthest from the primacord was less damaged. Later, they were able to reprogram both sun sensors to work at the reduced sensitivity, but Manning said that it had "sunglasses" on for the entire mission. (Buck) said that the issue of particulate leakage from the Delta PAF spin-down yo-yo pyro panel had been considered during MGS reviews, but not on Pathfinder. He said that we need to disseminate information on launch vehicles and ICDs when more than one vehicle is being planned during a short time frame, especially because we are making a habit of launching Deltas in pairs like Mars '98 and Mars '01.	Program-to-program interchange of Information can prevent big problems	1. (Implied) Develop a managerial process for technical interchange between programs - possibly mandatory attendance of selected project personnel at the program reviews of another project.
Conveying Lessons Learned through Formal Practices Documents.	(Buck) (Pathfinder) based on MPF and other spacecraft developments:		(Buck) Policy: • We need a good design practices manual.

Table 2 - Common Threads - Hardware Interfaces

Common Thread	War Stories	Lessons Learned	Corrective Strategies
General Hardware Configuration Issues.	**1.** <u>PF Documentation</u> (Manning) Regarding a rapid development program like PF, Manning said that being quick on your feet is important. PF was weak on documentation. Half the requirements were defined and agreed to in the hallway. They rarely went back and formalized the paper documentation. They used e-mail messages to record (document) a lot of agreements. **2.** A question was asked by Mona Witkowski related to the earlier CT Workshop finding about (poor) documentation of interfaces leading to problems. How did PF handle interface documentation? **3.** (Manning) Interface Control Documents (ICD) are so important and were a definite exception to their minimal documentation rule. You need as-built documentation. **4.** (Manning) Pathfinder. Carl Buck was responsible for interface and as-built documentation By previous standards, the functional documentation was minimal, and was largely paperless. The entire EDL was described in about ten pages, and this was their functional sequence documentation. It was useful as an overview of what they wanted to do, but not as a source document. Their baseline source documentation was a "giant" computer program which was augmented with source material like tables of atmospheric constants, gravity tables, parachute aerodynamic properties, etc. for the Martian encounter. These were their baseline system documentation; the paper documentation got the ball rolling and was essentially discarded. The paper documents weren't updated. (Manning) Galileo had a Command Data System (CDS) Hardware/Software interface document that defined about everything you wanted to know. It defined the as-built configuration, and everyone used it. They emulated this approach on PF.	1. (Manning) These were the most needed and used documents on PF: circuit data sheets schematics source code mechanical ICDs CAD drawings 2. (Clawson) (MPF) Mechanical ICDs weren't updated which led to problems	1. (Manning) (Implied) There is a critical minimum level of documentation which must be maintained. This would include: circuit data sheets schematics source code mechanical ICDs CAD drawings 2. (Clawson) (Implied) Interface Documents must be updated.

Table 2 - Common Threads - Hardware Interfaces (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
General Hardware Configuration Issues.	(Buck) Pathfinder Configuration Management • ATLO bore most of the CM responsibility and labor. The PF Project O.K.'d release of red lines. There was uncontrolled risk here. We shouldn't have to do this. • They pulled people quickly at the end of PF. As a result, about 70 configuration control items were not finished.	(Buck) (Implied) There is an essential minimum Level of Configuration Management for all programs.	**(Buck) Configuration control:** • Do as little as you can get away with, but do enough. • Pay attention to the MICDs. • CM needs to be user-friendly. New automated CM tools are being implemented by DNP/DBAT. • Assign a CM representative to work with the configuration team on the project.
Spacecraft/ Launch Vehicle Interface Errors	**<u>Atlas Push Test</u>** (Slonski) discussed the infamous (and possibly apocryphal) Atlas Push Test which purportedly occurred in the late '50s or early '60s. As a final test of gyro phasing, they used to have an operator on the gantry push on the rocket in two quadrants while someone in launch control (who probably couldn't see the operator) watched the gyro response on the instruments. In this incident, the person in launch control saw his instruments move in the wrong axis. He called the operator and told him he must be pushing in the wrong quadrant, whereupon the operator pushed the other way, satisfying the person on the ground, but completely ignoring the fact that the gyros were sensed wrong. The missile had to be destroyed when it launched out of control.	(Slonski) Look at everything. Investigate unexpected results.	(Implied) Thoroughly investigate any deviation from expected results. These are the results that provide the most information.

Table 2 - Common Threads - Hardware Interfaces (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Spacecraft/Simulator Interface Errors	**<u>(Manning) (Pathfinder) Victims of their own Success</u>** A question was asked: Why don't the computer reset problems show up on the Test Bed? Manning answered that they have been able to reproduce the problems on the Test Bed. The problem with the lander computer resetting is due to the high data rates (8,295 bits/second) that they have been running. The computer simply goes into processing overload and shuts itself down. They try to run at the highest data rates, because they achieved a +/- 1 degree accuracy in earth pointing angle. The spec was +/- 3 degrees. The upside is that they were able to process more pictures and downlink more data. They knew that under worst-case processing speeds the computer would reset and it did.	(Wirth) observed that it is important to test for the "best" case in ground tests as well as the worst. Manning replied that they had, however the best case for one variable is sometimes the worst for another.	Simulate all viable scenarios and worst case conditions in ground tests.
Spacecraft/Simulator Interface Errors (Continued)	(Wood) (Pathfinder) Flight Hardware development was driven by a goal of subassembly deliveries to SAF without sufficient attention given to integrating the subassemblies into a verified and calibrated communications system. The AIM software was tested in the test bed before launch, but it wasn't integrated with telecom and the DSN. It needed to be. There was no telecom capability in the test bed to assure integrity of sequence and no emulation of DSN actions and response times. As a result, operational readiness tests were useless in this regard.	1. (Wood) (Implied) Simulation of the DSN interface and operations in Operational Readiness testing is essential. 2. (Wood) (Pathfinder) The operations interface with the DSN is cumbersome and prone to misunderstandings. 3. (Wood) Late deliveries of Ops schedules, sequences and keywords are difficult for DSN Ops to keep up with.	1. (Wood) (Implied) Include the telecom interface and DSN operations in Operational Readiness testing. 2. (Wood, Komarek) Do end-to-end testing of the telecom link. 3. (Wirth) Test beds should include more things - specifically with respect to the telecom - DSN interface.(Wood) (Implied) Use a single point of contract with DSN. Involve DSN early and keep them up-to-date on changes 4. (Komarek) End-to-end testing is essential. There is always some RF interference and leakage. We need to extend the "ends" as far as we can. With the advent of smaller and smaller systems, an anechoic chamber is feasible and might be a good investment for the Laboratory.

Table 3 - Common Threads - Contractual Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
The Prime Contractor Generally Lacks the Technical Depth of JPL.	**<u>Topex Transponder</u>** (Komarek) (Topex) Although Topex was a highly successful program, Komarek believes that closer monitoring of the radio subcontractor would have saved time and money. There was an 18 month delay and several million dollars spent in correcting preventable problems, but JPL was reluctant to get between the prime and the subcontractor.	(Implied) Monitor Subcontractors Closely.	(Implied) Don't be afraid to step in if a Prime contractor/subcontractor relationship isn't working.
JPL/ Contractor Relationships Have a Spotty History; Some Work Well; Others Have Not	1. **<u>Working with Vendors</u>** (Buck) (MPF) discussed problems they had with vendors: <u>Small vendor issues:</u> • Low volume production on S/C systems causes lack of clout by JPL **<u>Large contractor issues:</u>** There tend to be differences between JPL and the internal practices of prime contractors. Carl mentioned several: • KEENSERTS are not O.K. for ATLO because they need to be backed out for repair and rework, but are a standard approach at Martin. <u>CAD databases:</u> • There are database transfer issues when JPL and the vendor don't use the same CAD system. On SIR-C they couldn't convert to Computer Vision. On Pathfinder, it wasn't much of a problem. • In the future, be careful to use the same platforms as the prime contractor; otherwise use paper! • (Guarino) Need to know about control of subcontractors and vendor monitoring • We are headed toward a lot more subcontracts.	1. (Buck) Pathfinder posters and buttons went a long way in building allegiance from the vendors.	1. (Guarino) Need to have lessons learned as to successful and failed tactics. 2. Suggestion: Focus groups on specific issues

Table 4 - Common Threads - Heritage and COTS Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
General Heritage Issues.	<u>Technology Transfer to Future Programs</u> 1. Alison Weisbin asked whether the PF process will be transferable to other programs. She specifically mentioned the balloon concept for soft-landing the spacecraft. Manning answered that he didn't know whether the balloon lander approach would be reused, but that much of the Pathfinder technology will be transferable to Mars '98. He mentioned that the computer, the aeroshell, much of the electronics and the parachute will all be used on Mars 98. This is the main reason Mars '98 can be done much cheaper than PF.	1. Heritage reduces costs. 2. (Implied) Documentation is the way to do it.	(Implied) Move people and documentation to new programs to facilitate heritage.
Placing too much trust in Inherited Hardware.	(Slonski) (Magellan) If there is a common thread in Slonski's experience it is: "Never trust a Star Tracker!" The Magellan Star Tracker was a notorious example. They anticipated the possibility of the Star Tracker tracking particles of debris, so they waited two days into the flight to make sure all the debris was out of the way. It wasn't enough. First the Star Tracker picked stars that had different brightness than those they had programmed. After they fixed that, they expected to see two stars at the selected intensities. They saw other "stars" too. Protons from the solar flare that occurred at that time triggered the Star Tracker as false stars. With the increased solar activity, the Star Tracker looked a lot like the digital equivalent of a Geiger counter. They reprogrammed so that most of the time, the Star Tracker would ignore blips from protons. When they weren't seeing solar activity, the spacecraft manufactured "stars" which they attributed to Astroquartz particles from the thermal blanket moving in response to surface charge shifting as they moved in and out of the sun.	1. Star Trackers have been Notorious Problems 2. (Slonski) "Don't Turn Your Back on a Star Tracker! 3. (Slonski) Star Tracker problems were one of the worst problems on Magellan. The new ones are supposedly better, but that will take years of "perfect" performance to be proven	1. (Slonski) Star Trackers are insidious. Don't trust them.

Table 4 - Common Threads - Heritage and COTS Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Placing too much trust in Inherited Hardware. (Continued).	(Slonski) (Mariner '69) **Relay Problems** The Star Tracker on Mariner '69 had two relays that were supposed to step through five cone angles. The logic sequence was determined by routing command signals through the relay contacts. The relays would go from Step 1 to 2 O.K. Step 2 to 3 was O.K., but when they commanded it to go to Step 4, the relays would revert to Step 2. Locked in those angles, they were limited in acceptable stars to track. They selected the Large Magellanic Cloud as the most usable light source, but it is very weak and diffuse. The Photomultiplier went to maximum gain and got the equivalent of "eye strain." They knew that if they left it in that condition, they would eventually lose the photomultiplier tube. They sent the command to change gain nine times without success, but the tenth time was a "charm." They believe they dislodged a particle on the relay contacts and then the cone angle changes worked. Mariner '69 (Miles) (Mariner '69) Because of the possibility of the Star Tracker tracking debris and outgassing, they decided not to turn it on for four hours after launch to give the system time to outgas. It wasn't enough. They still had problems with false targets.	1. (Implied) Don't use relay logic that can't be independently controlled. 2. Star Trackers have been Notorious Problems	(Slonski) Make sure spacecraft discrete functions are set by absolute commands from the ground
Placing too much trust in Inherited Hardware. (Continued).	(Komarek, Wood) (Pathfinder) Major elements of telecom flight hardware were adopted from Cassini with insufficient evaluation of the resulting capabilities and adaptability to the PF mission. • Auxiliary Oscillator phase noise spectrum degrades telemetry. • Trigger happy command lock detector has serious side effects. • Telemetry Modulation Unit unintentionally employs wrong code. • Ranging metric performance was marginal for Mars arrival	(Komarek) Heritage doesn't mean everything. Hardware may not work in a new application with new mission requirements. For example, the Auxiliary Oscillator has a back up capability on Cassini, the Ultra Stable Oscillator (USO). There was no USO on Pathfinder.	1. (Implied) Perform an intensive review of the mission differences between the donor program and the recipient program. 2. (Implied) Don't assume that inherited hardware is O.K. Analyze it and if the new application is significantly different, qual test it as if I were a new design.

Table 4 - Common Threads - Heritage and COTS Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Trying to Make Something that's Good Enough a 'Little Bit Better'.	(Komarek) The transponder is the heart of the radio containing transmitter, receiver and digital electronics. He said it is very much like a cellular phone, but it is special purpose and high sensitivity. It is produced in tiny numbers so it is very expensive. You can't buy one at Radio Shack! **<u>Magellan Radio</u>** (Komarek) (Magellan) Motorola reworked some ground straps to cure a suspected soft ground condition, but ran into many problems. For instance, the resoldering resulted in solder flow underneath the boards where it caused shorts and couldn't be inspected. The rework cost $200K. <u>Mars Observer Radio</u> (Komarek) Mars Observer (MO) later wrote a contract to GE who contracted with Motorola to fix the ground strap problem on MO. There were no problems with that rework, largely due to the "blood and sweat" on Magellan.	1. (Komarek) believes the cure was worse than the disease and that the rework probably wasn't needed. 2. (Implied) Once a difficult problem is solved, stick with the solution.	1. (Komarek) "Take rework decisions very seriously and weigh the costs and hazards of rework against the potential mission improvement."

Table 4 - Common Threads - Heritage and COTS Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Trying to Make Something that's Good Enough a 'Little Bit Better'.	(Manning) (Compton) Mars Pathfinder had to perform a test at China Lake Naval Weapons Center (NWC) that they considered a "check mark" test, i.e., a test they were sure they'd pass because they were using 'proven' rocket motors. They strapped on real retro rockets to a simulated aero-shell and dropped the system out of a helicopter. The rockets fired, and their first impression was that they had worked properly. However the only data they got was from the NWC laser optical tracking system, because the parachute didn't work, and the on-board measurement system was destroyed on impact. Weeks later, the China Lake crew found that the power to the DRAM was still on, and they were able to salvage the data in the "destroyed" recorder. Much to their surprise, they found that all three rocket motors had a burn anomaly, apparently through some complex acoustic-dynamic coupling through the simulated back shell. They never did understand the physics of the relationship between the acoustic and dynamic coupling that caused the anomaly. Prior to this, they had switched the propellant from 16% to 2% aluminum in the solid rocket motors to reduce aluminum contamination at the Mars landing site. While they were investigating the test failure, they asked what the function of the aluminum was. They were told that is was a vibration damper. Ultimately they switched back to 16% aluminum. The whole process, from identification of the problem to delivery of the redesigned rockets took only 30 days. They took the flight spare back shell and tested it with new rockets on a tether and proved there wasn't a problem. Manning said that there are very few real pyrotechnic experts left. This is also true of the rocket manufacturer. The manufacturer's personnel were very accommodating in making changes to the aluminum concentration, but weren't able to provide much help in anticipating the effects of proposed changes. Manning felt they needed better access to propelllant/pyrotechnics expertise on the PF program and was concerned that we might be losing it as a national resource.	1. (Manning) There is a lack of propellant expertise at JPL. There is also an apparent lack of such expertise in industry. 2. (Manning) (Implied) It is important to run even the "check mark" tests, i.e., those that have every expectation of being successful. Sometimes they are not, and sometimes they turn up unexpected and important results. 3. (Implied) "Minor" changes can lead to major problems. In this case, the people making the change in propellant mix didn't possess the necessary expertise to evaluate all of the consequences.	1. (Implied) Reacquire a source of pyrotechnic expertise at the Laboratory. 2. (Implied) "If it ain't broke, don't fix it,", i.e., Think through all the ramifications of proposed changes and weigh them against the expected benefits. 3. (Implied) When changes are made in esoteric technical areas, get an expert's advice.

Table 5 - Common Threads - Parts Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Unique Part Types are a Problem	1. **<u>Gyros and Tape Recorders.</u>** (Clawson) (MPF) stated that they had compiled a list of flight failures on prior JPL missions and two items which came up as potential failures were gyros and tape recorders. They didn't have any gyros or tape recorders on PF. 2. (Manning) (MPF) stated that in his experience that the failure rate on NASA Standard Initiators (NSI) was negligibly low. He thought that the dual redundant NSI string on MPF might be overkill. 3. (Clawson) still wouldn't use single-string NSIs.	1. (Implied) Good system design can eliminate the need for high failure rate devices. 2. (Implied) Some functions are so mission critical that they demand redundancy even if they are highly reliable.	1. (Implied) Try to avoid high risk components by system design whenever possible.
Unique Part Types are a Problem (Continued)	(Marr) (Galileo) The problems that occurred with the TC-244 memory chips turned out to be fortuitous. The TC-244's were changed out and replaced with 1K RAM chips. As a precaution, Tom Gavin, the Product Assurance Manager, made sure that the on-board memory was doubled. Without the added memory, they wouldn't have been able to do any of the data compression. Their best estimates were that they would need 4 to 8K of RAM. They put in 32K and thought that would be plenty. As it is now, the whole system is packed to the limit.	Sometimes a problem turns into a solution.	Marr's Admonitions: • You need plenty of memory • You need plenty of CPU speed. • You need plenty of band width. • You must do whatever you can to achieve this.
Unique Part Types are a Problem (Continued)	1. (Reh) mentioned the Cassini inheritance of ASICs to other missions. Multiple program usage can give substantial leverage and save money by increasing the number of items purchased.	(Reh) Buying in greater quantity provides leverage, but there needs to be Phase A and B (i.e., Conceptual phases) coordination of projects to take advantage of potential multi-use ASICs.	(Implied) Pool resources of several programs to fund technological advances that are useful to both. (Reh) Coordinate multiple-program needs for ASICs and special purpose parts early in the development cycle to take full advantage of larger parts buys.

Table 5 - Common Threads - Parts Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Misapplication of Parts	1. (Carpenter) said that fabricators still run into problems in which the CAD designer uses one part footprint in the design layout and purchasing buys a different part layout. The problem isn't found until the boards and parts meet in packaging and can't be assembled.	1. (Carpenter) There are still coordination problems because purchasing and the designers use different part footprints. The design function and procurement function have to work from a common data base.	1. (Carpenter) Establish a common database so part footprints are common between design and purchasing. 2. Make sure parts can be purchased and are available. 3. Use simplified procurement specs; they have used IPC specs very successfully. 4. Use qualified vendors.
Radiation Environments are a Special Problem.	1. **(Manning) (MPF)Single-Event Upsets** They have experienced no single-event upsets (SEU) to date on Pathfinder. At least, there have been no double faults in a single word. They have single error correction - double error detection and so would be able to detect a double bit error. In fact, they have had no DRAM problems at all. Manning said that we've come a long way from the TC244 problems on Galileo. On Galileo, they spent millions hardening the TC244 chip which wasn't intended to be a RAM chip in the first place. 2. (Clawson) SEU Upset Rate: • The best estimate they had on PF was several a day on DRAM. • Clawson now asking "What do we really expect?" • Unknowns in the environment are on the order of a factor of 2 • Unknowns in the effects are on the order of 10 to 100 • The most likely number is that they should have had 1.2 SEUs by now. The probability of zero at 8 months is about 30%.	1. (Clawson) (MPF) The modeling process for calculating SEUs appears to be overly conservative.	1. (Implied) A review of the methods for estimating SEU rates appears to be in order.

Table 6 - Common Threads - Programmatic Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Increased "Sell" Pressure on Programs to Provide More Performance at Reduced Cost on Tighter Schedules.	1. (Manning) Rob had been involved with Galileo and Cassini, primarily with the ACS and CDS subsystems. He said that there was really never any question during those developments about whether the missions would ultimately succeed. He referred to PF as a "scary ride." They were always uncertain about whether the systems would work or not. 2. (Komarek)) We are going through a "gutsy" period at JPL. Several projects are assuming substantially higher risk than we were previously willing to take. We won't be able to repeat this very often, because there is a need to continuously develop the science. He said that the 8.4 - 11 kHz communications link that was adequate for Pathfinder isn't fast enough for future projects.	1. (Implied) FBC programs often involve a higher risk than JPL has taken in the past. 2. (Komarek) We won't be able to repeat the Pathfinder experience very often, because there is a need to continuously develop the technology to collect better and more accurate scientific data.	(Komarek) We need to reinstate our commitment to depth, discipline and rigor in support of the sciences and develop the new tools we'll need to do it.
Program Reviews	(Buck) (Pathfinder) **Little Stuff**: There were miscellaneous hardware items that escaped review. The issues were raised so late that PF was flown without a desirable feature rather than risk failure due to inadequate review. • Planetary Protection Cover Doily. They didn't consider this until too late. They flew with no cover, because they couldn't get everyone together. • They needed an RF absorber for in-flight test of the radar altimeter, but overlooked it.	(Buck) No flight hardware item is too small for peer review!	(Buck) (Implied) Subject all flight hardware, even the least significant to peer review early enough to correct any issues raised.

Table 6 - Common Threads - Programmatic Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Concurrent Engineering Teams/ Collocation Issues	1. (Manning) (Pathfinder) They had a team taken from six JPL Divisions • Created their own mini-Division • People interested in what's going on the other side of the wall • Needed strong thermal and telecom engineers in the beginning, but didn't have them 2. (Manning) (Pathfinder) said that a good development program matches the design to the people and processes you have available. 3. (Manning) Pathfinder gave broad freedom to the developers to do what they needed. They encouraged everyone to think with a systems perspective, i.e., to look across interfaces to solve the whole systems problem. The engineers rose to the challenge; they invented the process as they went along, and it worked.	(Implied) The approach used on Pathfinder which emphasized a strong development team, concurrent engineering, system-level thinking, adapting the people to the design and the design to the people worked very well and can be emulated on future programs.	(Manning - Compton) (Pathfinder) • Program Managers have to lead, not just administer their program. • Cog E's must go across their interfaces • Keep a systems perspective • People must be given freedom to go beyond their charter •Take advantage of the skill mix and processes you have available. •Make sure you have an adequate skill mix early in the program. •(Clawson) Infuse flexibility into processes.
Concurrent Engineering Teams/ Collocation Issues (Continued).	(Manning) (Pathfinder) Their fundamental mechanical problem was mounting a bunch of "square" electronics boxes into a tetrahedron. Collocation facilitated concurrent engineering. Ultimately, they moved the electronics engineers into Building 230, so these kinds of packaging decisions could be made quickly. They used the Mentor/Cadence tools. Almost everyone was right there to make on-the-spot decisions. Lack of money led to lots of ingenious solutions. The result was good but not "pretty."	1. (Manning) referred to an "intellectual critical mass" of technical interchange that exists which is greatly enhanced by collocation.	(Manning) (Implied) Collocation should be encouraged if it is feasible to achieve it.
Concurrent Engineering Teams/ Collocation Issues (Continued).	(Wirth) (Pathfinder) said that they also found out after launch that the Sun Sensor window was obscured by the cabling. He noted that the persons working Configuration Management both at JPL and Martin occasionally got confused as to whether they were talking about PF or MGS.	(Wirth) It is difficult for one person to work multiple similar programs (e.g., MGS and PF) at one time. They tended to get confused about which one they were talking about with the vendor (Martin).	(Wirth) (Implied) Avoid overloading personnel with concurrent assignments that could be easily confused.

Table 6 - Common Threads - Programmatic Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Concurrent Engineering Teams/ Collocation Issues (Continued).	**(Komarek)** Design Issues There needs to be more concern for systems engineering. There is a very tight focus on the hardware, but not so much on the systems. The hardware technologists and subsystem designers need to be aware of the whole systems design process so that key mission issues are considered in their designs. The projects need to involve them.	1. (Implied) System involvement by the technologists could prevent problems and help develop more creative solutions.	1. (Implied) Get everyone to think "system." 2. (Implied) Projects should take positive actions to involve technologists in the design process.
Concurrent Engineering Teams/ Collocation Issues (Continued).	1. (Komarek) (Pathfinder) Collocation is essential for our success, especially on FBC programs, however accomplishing this is not so simple. There are more projects than there are section (experts) working in a technical discipline area. There needs to be sharing of these personnel among projects, so although collocation is an ideal goal it is often logically and practically impossible. The burden of proof for collocation must be borne by the Projects. 2. (Komarek) (Pathfinder) Even without collocation, there needs to be a closer link between the projects and the line organizations. JPL is not set up for meaningful dialog at this interface. The project people rarely come around to see the line organizations. The line organizations need involvement and emotional support even if they don't collocate.	1. (Komarek) Collocation is a good thing but hard to accomplish. 2. Komarek believes the telemetry problems on MPF could have been avoided with collocation.	1. (Komarek) There needs to be a closer link between the projects and the line organizations. 2, (Implied) Collocate the telecom personnel if possible.
Concurrent Engineering/ Teams/ Collocation Issues. (Continued)	Kim Reh (MPF, Cassini, DS-1) spoke from his experience in Avionics Development. 1. (Reh) (Cassini, PF, DS-1) We need funding from the "get go" or we lose credibility with contractors. 2. There need to be clearly defined technology cut-off dates. Going with too many interpretations results in misunderstanding and serious delay problems. 3. Reh asked; "Are we doing the right thing about the PEM role?" he believes that the PEMs were very good technically, but not so good in managing schedule and funds.	1. Strong and decisive Project Management = Tough love is in. Strong managers and systems engineers are needed 2. New technologies must be continuously "sold." 3. Use a rigorous approach to select technologies in Ph. A/B. 4. Base high tech missions on realistic constraints and bold challenges. Don't over-constrain the design process.	1. Get commitment from the Project Office on the objectives of the development/mission. Create "TEAM" ownership. We need to emphasize leadership and team building. 2. We need a "mentoring machine" for the Laboratory. 3. Staff to develop a TEAM environment. Get them in early and rotate them through the program phases. Provide career path opportunities. 4. Maximize communications 5. Get the systems engineering function in-place in Phase A/B. There needs to be an Avionics Systems Engineer who pulls together the H/W and S/W..

Table 6 - Common Threads - Programmatic Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Concurrent Engineering/ Teams/ Collocation Issues. (Continued)	4. (Manning)interjected that PF needed Division-wide responsibility for PEMs) 5. (Reh) believes there were too many contractors to manage the DS-1 3D stack program effectively. The design was too complex which led to cost overruns and late deliveries. 6. We need better project management and system engineering tools to manage complex developments.	5. Challenge requirements and implementations. 6. Leverage industry but minimize the number of contractors 7. Electronics designers need to use behavioral models to exercise system concepts before breadboarding.	7. Don't design the flight computing architecture without involving the software people. 8. Conduct frequent peer reviews We are not following up on peer reviews. We need to follow up and close out action items. 9. Solve problems as a team
Concurrent Engineering/ Teams/ Collocation Issues. (Continued)	1. (Reh) (Cassini, PF, DS-1)Line Management must be part of the Development Team: Kim asked "Where is the team between line management and Projects?"	1. (Implied) Project Teams and Line Organizations have a different view of team effectiveness 2. (Reh) We need to emphasize leadership and team building.	1. (Reh) Staff to develop a TEAM environment. Get them in early and rotate them through the program phases. Provide career path opportunities. 2. (Reh) Line management needs the support of the Project Team members. 3. (Implied) Empower Project Team members and work with them, not above them. 4. Let young Project Team members share in the "limelight' when the mission succeeds. 5. Engage the public by personalizing the Team and the science.
Concurrent Engineering/ Teams/ Collocation Issues.	1. (Clawson) was involved with both the Pathfinder program and the Apollo 11 Mission to the moon which was a NASA-wide team effort of historic importance. He considers the team effort on Pathfinder to be even stronger than that on Apollo 11, and he compared the excitement of the July 4 landing of Pathfinder to the first Apollo moon landing. 2. <u>**.Naming the Rocks**</u> (Manning) (Pathfinder) joked that it was only a rumor that there was a NASA plot to name the rocks on Mars after cartoon characters in order to get more money. Clawson said that there had been a tremendously positive effect on young viewers because of it. Cartoon names - instilled the interest of children. It has been great publicity.	1. (Implied) Teamwork and Esprit de Corps produce better systems.	1. (Reh) Get commitment from the Project Office on the objectives of the development/mission. Create "TEAM" ownership. Do what's good for the <u>*team.*</u>

Table 6 - Common Threads - Programmatic Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Budget and Schedule Reserves on Faster Better Cheaper Programs.	1. Pathfinder Test Program (Manning) Testing dominated the Pathfinder program. They wrote a test plan, but couldn't hold to it. They simply couldn't anticipate all the tests they would need at the beginning of the program. Approximately forty percent (40%) of the flight system development budget was reserved for unplanned activities that evolved as the ATLO program progressed. As an example, when they became concerned about the effect of a possible Mars hard landing (45-50g) on some relays, they piggy-backed a relay test on an accelerometer shock test to make sure the relays were O.K. This kind of thing went on continually during ATLO.	1. (Manning) (Implied) The big dollar and schedule reserve on Pathfinder allowed them to adapt the test program as new results and problems occurred.	1. 1. (Manning) (Pathfinder) Advice for FBC Programs: • Allow a big budget reserve. • Plan/expect a big test program • Replan the test program as the program develops.
Hardware/ Software Integration Issues	1. (Marr) stated that software issues are normally not given the same level of attention as hardware issues. This situation will necessarily change. As systems become more complex, software issues become increasingly important. The SIMS, for example, will have 100,000 lines of "C^{++} code. This is a system as large and as complex as the hardware. Imbedded software systems need as much attention as does the hardware. 2. (Marr) The Develop New Products (DNP) reengineering program hasn't really thought much about software. The focus has been on the mechanical and electronics engineering issues in the hardware.	1.. (Marr) As much attention must be given to the software development as to the hardware development.	1. (Marr) made several recommendations: • Software development has to be run as a project with all of the appropriate project controls. • Get the software designers involved early. • Software prototyping has to start early, just like the hardware. • Flight and ground software has to be treated like a system, with a proper partitioning of functions between the two entities. • The software development has to be staffed with a strong team
Hardware/ Software Integration Issues (Continued)	**Galileo Tiger Team** After the failure of the Galileo High Gain Antenna to deploy, Marr co-chaired the effort to recover the bulk of the critical mission data using the 7 bps data stream from the low gain antenna. The solution led to an end-to-end redesign of the DSN, as well as the spacecraft software. Doing this required data compression ranging from 10:1 to 50:1. They averaged somewhat greater than 10:1. They arrayed as many as six antennas at once, at Goldstone, Parks and Canberra in order to get the data down. It was necessary to greatly improve the bit error rate to achieve the needed compression with data integrity. They have achieved a bit error rate of better than 1 in 10^7. They also completely redesigned the CDS software to achieve the data compression. They reprogrammed eight of the eleven science instruments. This was a huge effort involving 150 people, half on the spacecraft and half on the DSN. They initially decided to deliver the software in three phased chunks about six months apart. This didn't work. After delivery of the first chunk, they went to	1. (Marr)Software complexity rivals hardware complexity. 2. (Marr) Multiple test beds were essential to training personnel for their roles in downlinking the data on the rapid development project.	1. (Implied) Consider using multiple test beds to permit concurrent software development and speed up the development and training process.

Table 6 - Common Threads - Programmatic Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Hardware/ Software Integration Issues (Continued)	a phased delivery in which they delivered weekly. This worked beautifully, creating a tight loop between the developers and the testers. The developers got immediate feedback on the results of software changes. The spacecraft had to continue operation during the development process. There were two complete test beds, plus there was another FASTSIM bit level simulator on a UNIX work station. They were able to perform 20 different tests concurrently, and Marr said that the process worked wonderfully. As it was, there were 20 different imaging modes, and they all had to be checked out. They added the capability to run all instruments and interface with the telecom.	See above.	See above.
Hardware/ Software Integration Issues (Continued)	(Marr) (DS-1) **Autonomous flight presents a host of new problems.** The advent of autonomous flight software introduces a new level of thinking. Ultimately it will drive ground software up again, but to do other things. There has been a tacit belief that "We'll find a way of fixing hardware problems in the software." We need a better way of partitioning functions between H/W and S/W to optimize the system and we need to develop tools to do that. **DS-1 Crisis Tiger Team** Marr received an IOM from Joe Savino to form a Tiger Team to help Dave Lehman with a schedule problem on DS-1. The Tiger Team was to be a two-week effort. This is a key new technology: Remote Agent Flight Software. They were 9 months behind. Charles Elachi had directed them to do what was necessary to launch on time. The team took two weeks to look at all the available options. They found that the Remote Agent team was approaching their job from an "all or nothing" perspective, i.e., demanding full spacecraft autonomy with no ground intervention whatever, and wouldn't communicate with the integration team. The Remote Agent team, the Core Engineering team and the Test team were "locked in a fatal embrace." Tests were being run on three different sets of hardware. The Remote Agent team was turning over the software to the Test Team, but wasn't helping in the integration. The lessons learned resulted in a number of actions.	1. (Marr) The Tiger Team implemented several corrective actions which were ultimately successful: • Descoped to a single RAD 6000 processor • Fell back to the core PF code with a few autonomous functions • Relegated the Remote Agent capability to an in-flight experiment. • Implemented the phased delivery approach. 2. (Marr) With these corrections to the process, it now looks like they will meet the launch date. 3. Joe Savino has prepared a memorandum noting with about 30 lessons learned from the DS-1 experience.	1. (Marr) As a result of this Tiger Team effort, the Integrated Product Development Team (IPDT) will switch to an incremental software delivery approach in the future. 2. (Implied) Appreciate that autonomous flight software development creates a host of new problems. 3. (Implied) Review Savino's lessons learned list for applicability to new programs.

Table 7 - Common Threads - ATLO and Launch Site Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Moving to the Cape with Incomplete Procedures and Without the Necessary Personnel to Make Decisions Quickly.	1. (Wirth) (Launch Activities) Vince presented lessons learned in preparing and launching a spacecraft at KSC. The objective is to minimize time at the Cape. which is a big cost driver. Wirth said that the "Must Do" activities don't make a very long list, but a lot of "Like to Do" activities get added that extend the time at the Cape. The big problem is telling the difference. He cited some examples: • Why is it necessary to run Final System Test at the Cape? If we don't have confidence that the spacecraft can survive the transportation environment, how do we justify launching it into a harsher one? • DSN compatibility testing. With the new DSN trailer, there should be no reason for any testing with DSN 71. Additionally, the environment can lead one astray. MGS was chasing non-existent command problems that were due to local multipath. • Spin table and CG operations. The advent of 3D computer models sensitive enough to identify the off-set in CG caused by one extra bolt would seem to eliminate the need for doing this at the Cape. 2. (Buck) (Pathfinder) Carl called it a myth that a spacecraft can't be spin-balanced with propellant in the tanks at KSC. They do it routinely on other programs and they did it on Pathfinder. 3. (Gibbel) Vince Wirth had ATLO School for the people involved in the PF T&E program.	1. (Wirth) <u>Design Issues:</u> • A person knowledgeable about KSC should be a member of the design team. • Remember that testing and verifying full range deployments of appendages at the launch site is slow and expensive. 2. (Implied) An unwarranted desire to verify as much as possible as late as possible leads to unnecessary complication of pre-launch activities at the Cape.	1. (Wirth) Do the "Must Do" activities at the Cape: • Propellant tank loading must be done at the Cape - dictated by safety. • Pyro installation, arming and checkout - again dictated by safety. • Final close-outs of blankets, etc. • Mating with the launch vehicle. 2. (Wirth) (Implied) Minimize the "Like to Do" activities. 3. (Wirth) The spacecraft should be designed so that the transported pieces are as few as possible, and the number of re-assembly operations at KSC is minimized. 4. (Wirth) Design the spacecraft so parallel operations can take place. 5. (Wirth) Make everything as accessible as possible. Extra effort and time are needed for blind connector mating and upside-down bolt torque. 6. (Wirth) The design should include some way of verification with partial or no deployment of appendages.

Table 7 - Common Threads - ATLO and Launch Site Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Moving to the Cape with Incomplete Procedures and Without the Necessary Personnel to Make Decisions Quickly. (Continued)	1. See Wirth's comments on the previous page. 2. (Reh) More fidelity in the testing pays off. They have had significant problems at the Cape.	1. (Wirth) Do as much as you can before going to the Cape 2. (Buck) (Pathfinder) No hardware should ever be assembled at the Cape without prior assembly at JPL. 3. (Buck) (Pathfinder) We need to do engineering walk-throughs of certain procedures at the Cape	• Use standard interfaces. This means that EVERYTHING is defined. This includes: data lines, voice channels, Internet capability, e-mail, facilities and all the other things the project will deal with. Any unusual or unique interfaces will tend to bring things to a crawl. • Plan the launch activities in detail. When doing this, remember to include other elements of launch activities. They may have more insight into how long something takes to accomplish and this can be reflected in a more realistic schedule. • Bring everything but the kitchen sink with you. Granted, the Launch Site Support Managers are good at finding most things, but don't take any chances. • Have picnics. This therapy is used to feed the social needs of the team who are under strain because of being away from home. Don't forget, the successful team includes the worker's family.
Safety Issues	(Wirth) Based on his experience with Pathfinder and other programs, Vince Wirth made observations on how to streamline and improve safety-related operations at the Cape.	1. (Wirth) Some key safety activities at the Cape can be combined, making them both more efficient and safer.	1. (Wirth) Separate the propulsion system from the electronics. In that way, the electronics can be tested while hazardous operations are taking place elsewhere. 2. (Wirth) If design precludes this, consider loading the propulsion system on the pad. Many commercial birds already do this. The rationale is that it is cheaper and faster to do all hazardous operations in one place - the pad.

Table 8 - Common Threads - Product Assurance Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Robust Design Issues on FBC Programs	1. Pathfinder Redundancy (Manning) Rob said there is a perception that PF was a "single string," i.e., non-redundant system, and that people were rightly concerned about that. While much of PF was single string, there was selective redundancy, and in fact, the PF mission was salvaged by redundancy in at least one instance. 2. (Slonski) (Magellan) Pathfinder Sun Sensors As Manning discussed, they lost both sun sensors on Pathfinder, but one was less damaged than the other and was partially usable. Ultimately they salvaged both sun sensors so they were usable. 3. PF Redundancy Determinations (Manning) (Pathfinder) People outside the MPF program probably don't fully grasp the enormous complexity of the mission, nor the extensive management effort it took to manage that complexity and to deal with the reliability issues. 4. (Manning) Reliability issues were handled subsystem by subsystem. He answered a question that was asked as to how they had managed the issue of redundancy on MPF. MPF had a simple process for determining which subsystems needed to be redundant. They formed a team of design and reliability people who estimated a "probability of breaking" for each subsystem as either low, medium or high. They considered the mission consequences of the failure as low, medium or high. They created a big spread sheet. Where there was a high mission impact and low reliability, they either reduced the probability of failure or made it redundant. Sometimes, they just convinced themselves that an item was intrinsically reliable	1. (Implied) Redundancy needs to be evaluated for FBC missions, including functional redundancy by different physical principles to avoid common cause failures. 2. Implied) Don't put all your eggs in one basket! Redundancy via a completely different physical principal can overcome common cause failures. 3. (Implied) Be aware of the possibility of common cause and cascaded failures due to common environments. 4. (Implied) Redundancy needs to be evaluated for FBC missions, 5. (Manning) (Implied) The team approach used on MPF to identify subsystems with high mission criticality was useful and could be adopted on other FBC programs.	1. Be aware of and design to avoid common cause failures, including those resulting from common environments. 2. (Implied) Use a Systems Approach to Redundancy. The team approach used on MPF which considered both the probability of failure and the consequences of failure for individual hardware element (FMECA) is a good way to perform such an analysis.

Table 8 - Common Threads - Product Assurance Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Robust Design Issues on FBC Programs (Continued)	5. They involved the designers by asking them questions like "If everything else in the system worked, and yours was the only subsystem to fail, what would be the most likely part to fail?" Based on their criticality, they decided they needed dual NSIs. 6. (Miles) (Mariner '4) They did a mid-course trajectory correction maneuver. They had programmed for two, but didn't need the second. 7. (Clawson) The Pathfinder reliability growth projections indicate that more problems should have occurred. A Pathfinder (PF) group is being formed to review the early program decision process to see what was done right so that important lessons learned can be carried over to new programs	6. See Above 7. Operational redundancy also needs to be considered. 8. MPF Reliability Program lessons are still being evaluated	3. See Above 4. (Miles) Redundancy issues extend beyond the hardware. Plan for more mid-course corrections than you really expect. Better to plan for more than not have enough. 5. Review the MPF Reliability Program lessons learned for applicability to new programs.

Table 9 - Common Threads - Fabrication and Production Issues

Common Thread	War Stories	Lessons Learned	Corrective Strategies
New / Miniature Technologies Bring New Fabrication Risks. Hybrids and Multichip Modules (MCMs)	1. (Carpenter) There are lots of smart young people involved in the new programs, but they are inexperienced and sometimes charge ahead without thinking decisions through. Lots of risk is being taken; in Dennis' opinion, some of the risks are not good ideas. Less rigor is being applied than in the past. We need to be really smart about risk assumption and management. 2. (Carpenter) There is lots of new technology in the packaging arena that poses new problems. Devices are smaller and harder to fabricate and inspect. Contamination is a severe problem. Ball grid arrays, for example, are difficult, because the solder bonds can't be inspected	1. (Implied) New technologies create new risks that must be carefully evaluated. 2. (Implied) Many of the old packaging issues still remain. 3. (Carpenter) Detail design and materials compatibility are crucial	1. Carpenter) We still need to design for manufacturability and reworkability. • Procure parts early • Involve Section 349 (Packaging) early in the Design stage • Select vendors carefully - let Section 349 help.
New / Miniature Technologies Bring New Fabrication Risks. **Instruments**	1, (Carpenter) Instrument technology now dominates. He mentioned "space cubes" and elastomeric connectors which he said had "horrendous" thermal problems. Testing is very important. 2. (Clawson) mentioned that PF had very good concurrent engineering in packaging. Dennis said that, even so, there were fabrication problems.	1. (Clawson) Concurrent engineering is a good idea for packaging issues. It worked well on MPF.	1. (Carpenter) Consider concurrent packaging engineering. Involve packaging engineers early. 2. (Implied) Recognize that new Instrument technologies may place severe demands on packaging.
Chronic Hardware Fabrication Problems - Some Caveats and Some Solutions **Printed Circuit Boards** & **Flexprint**	1. (Carpenter) said that there are far fewer problems with printed circuit boards than there used to be. Still, they run into problems in which the CAD designer uses one part footprint in the design layout and purchasing buys a different part layout. The problem isn't found until the boards and parts meet in packaging and can't be assembled. 2. (Carpenter) Flexprint connectors occasionally get laid out upside-down, leading to long delays for redesign and reprocurement	1. **Printed Circuit Boards.** (Carpenter) There are still coordination problems because purchasing and the designers use different part footprints. The design function and procurement function have to work from a common data base. 2. **Flexprint** • (Carpenter) Lessons learned are similar to those for printed circuit boards. • Terminals should be eliminated to save weight.	3. **Printed Circuit Boards** & **Flexprint** (Carpenter) recommends: • Establish a common database so part footprints are common between design and purchasing. • Make sure parts can be purchased and are available. • Use standard Gerber file formats. • Involve Packaging Engineering in the CAD process to prevent problems. • Use simplified procurement specs; they have used IPC specs very successfully. • Use qualified vendors. Stability in the industry has improved in the past few years, but turnover is still high. Recheck vendor capability frequently.. • Watch out for upside down connectors Stay away from terminals - they add weight.

Table 9 - Common Threads - Fabrication and Production Issues (Continued)

Common Thread	War Stories	Lessons Learned	Corrective Strategies
Chronic Hardware Fabrication Problems - Some Caveats and Some Solutions **Magnetics**	1. (Carpenter) No war story.	1. Magnetics can be long lead time items. 2. Magnetics vendors are not all equal.	1. (Carpenter) Ensure component footprint is compatible with the board 2. Standardize on uniform pin call outs. 3. Minimize potting volume to reduce thermal stress 4. Procure magnetic parts early 5. Use proven vendors
Chronic Hardware Fabrication Problems - Some Caveats and Some Solutions **Cable/Harness Fabrication**	1. (Carpenter) mentioned a situation on Wide Field Planetary Camera (WFPC) in which the braiding on a wire shield had silicone oil trapped in it. The vendors used to clean it with Trichloroethylene, but now they don't because of EPA regulations. The silicone oil outgasses in vacuum. His point was that "What worked yesterday doesn't necessarily work today." 2. (Manning) interjected that on MPF, they had one person who coordinated all the packaging issues. However, they didn't take control of the systems aspect of the cabling. They didn't have tools to see how the cables would be routed. This caused a large difference in the cable lengths to redundant NSIs. and several milliseconds difference in the firing times. 3. (Carpenter) said that tools are available now. He said that they didn't have a cable person collocated with the MPF design team. Design changes came fast, and the corresponding cable changes weren't always picked up. This led to a big rush to get a cable design during ATLO. Then, when the PF clamshell was closed, the cables interfered with the solar panels and had to be rerouted. 4. (Carpenter) said there is new CAD software that keeps an automated cable database that tracks with hardware design changes.	1. Cabling is often left as an afterthought, and it must not be. 2. There have not been tools that permit cabling to be tracked during the development process, but software is now available to do that. 3. What was good yesterday isn't necessarily good today	1. (Carpenter) Ensure cabling material is documented (jacket, braiding, connector, ties) 2. Ensure that material is vacuum compatible. 3. (Implied) Make sure the cabling design evolves and tracks with the system design.
Chronic Hardware Fabrication Problems - Some Caveats and Some Solutions **Interconnects**	1. (Carpenter) mentioned the problem on Galileo, in which the Solithane conformal coating got under the integrated circuit packages and worked the solder joints in thermal cycle until they failed. Increasingly, package weight is dominated by interconnects rather than the parts themselves.	1. (Carpenter) Solder joints have to be considered a "consumable." because they will ultimately fail with enough temperature cycling.	1. Quality assurance attention to ball bonding and wire bonding of hybrids becomes more important as package sizes decrease.

Observations on the Workshop

In the question and answer period following the formal presentations, several observations were made by attendees on the conduct of the workshop.

Christine Farguson could have used more depth in the specific examples (war stories) on which the advice being given was based. She also observed that the MPF project accomplished its mission, but at the expense of many 60 and 70 hour weeks. She asked if this was to be the wave of the future for FBC programs? Vince Wirth also asked that the CT Workshop speakers be directed as to what the format and expectations are, so that more war stories were offered as their basis for recommendations.

Steve Cornford offered what might be a good caveat for all of the lessons learned at the workshop. “The sum of all lessons learned tends to infinity.” His point was that, even though it is good to understand the lessons from past programs, no one can know them all. When faced with new situations, he advises: “Think before you act. Look at past lessons, but if the old guidance doesn’t work, don’t use it. Consider the root causes of failure and act accordingly.”

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